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Implementation and performance of the signal reconstruction in the ATLAS Hadronic Tile Calorimeter

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Abstract

The Tile Calorimeter (TileCal) for the ATLAS experiment at the CERN Large Hadron Collider (LHC) is currently taking data with proton-proton collisions. The Tile Calorimeter is a sampling calorimeter with steel as absorber and scintillators as active medium. The scintillators are read-out by wavelength shifting fibers coupled to photomultiplier tubes (PMT). The analogue signals from the PMTs are amplified, shaped and digitized by sampling the signal every 25 ns. The TileCal front-end electronics allows to read-out the signals produced by about 10000 channels measuring energies ranging from ~ 30 MeV to ~ 2 TeV. The read-out system is designed to reconstruct the data in real-time fulfilling the tight time constraint imposed by the ATLAS first level trigger rate (100 kHz). The main component of the read-out system is the Digital Signal Processor (DSP) which, using the Optimal Filtering technique, allows to compute for each channel the signal amplitude, phase and quality factor at the required high rate. A solid knowledge of the signal pulse-shapes and of the timing is fundamental to reach the required accuracy in energy reconstruction. Systematic studies to understand the pulse-shape have been carried out using both electronic calibration signals and data collected in the proton-proton collisions at $\sqrt{s} = 7$ TeV. After a short overview of the TileCal system we will discuss the implementation of Optimal Filtering signal reconstruction highlighting the constraints imposed by the use of the DSP fixed point arithmetic. We will report also results on the validation of the implementation of the DSP signal reconstruction and on the overall signal reconstruction performance measured in calibration, single beam and collision events.

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1. Introduction

ATLAS [1] is a general purpose experiment located on the Large Hadron Collider (LHC) ring. The LHC produces proton-proton collisions at a center of mass energy of 7 TeV. The Tile Calorimeter (TileCal) [2] of ATLAS is a sampling calorimeter made of steel as absorber material and scintillator tiles as active medium. The light produced in the scintillator tiles is read-out by wavelength shifting fibers coupled to photomultiplier tubes (PMT). The analogue signal from the approximately 10000 PMTs is amplified, shaped and digitized in the front-end electronics. The digital samples are transmitted to the back-end electronics through high speed optical links at the ATLAS first level trigger rate (100 kHz).

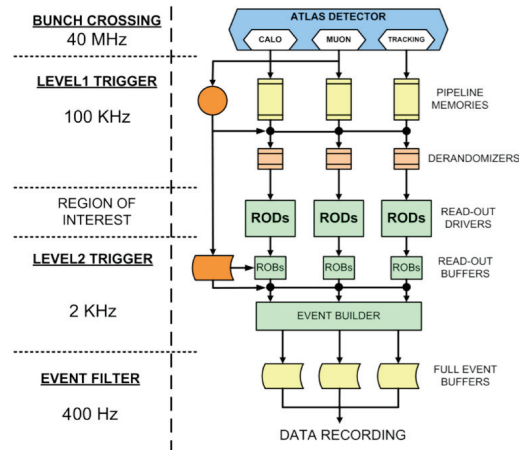


Fig. 1. ATLAS three level trigger architecture.

The Read-Out Drivers (ROD) [3] is the interface between the front-end electronics and the general data acquisition system (DAQ) of the ATLAS detector (Fig 1). The main function of the ROD is to reconstruct the signal amplitude and phase at the first level trigger rate and to transmit them to the DAQ system for offline analysis. The signal amplitude is also provided to the High Level Trigger to form the calorimetric trigger signals. Other important tasks of the ROD are: the synchronization of the detector data and the time of the trigger signal (Trigger Timing and Control Information [4]- TTC); the computation of total energy for specific detector areas; and the packing and transmission of all the digital samples for channels with amplitude above a configurable threshold for offline reconstruction which is particularly interesting in the case of pile-up events where an offline reconstruction could improve the signal reconstruction resolution. The core of the ROD are the Digital Signal Processors (DSP) that provide the high processing power required to execute these algorithms within the tight time constraint defined by the first level trigger rate.

2. Code Structure

The input stage of the code is composed by two circular buffers for data storage and one circular buffer for TTC data. When the data are received, the first task performed by the DSP is the synchronization between the detector data and the trigger information. Then, the DSP executes the signal reconstruction algorithm exploiting the Optimal Filtering [5] algorithm. The result of the reconstruction is used to compute information to be used to tag energy releases in TileCal compatible with a Muon signal

variations in any of these parameters. The weights are offline computed and downloaded into the DSP at configuration time.

The variation in the phase of pulses causes an underestimation of the reconstructed amplitude that can be parameterized. Therefore, the deviation produced by small phase variations within one bunch crossing can be corrected (Fig 3b). The energy generated in interactions of bunch crossings different from the one that has generated the trigger is indicated as out-of-time pile-up energy. This energy is not correctly reconstructed from the Optimal Filtering algorithm since it has a phase largely shifted from the expected one. This phase shift implies that the reconstructed energy is largely underestimated and therefore suppressed with respect to energy released with the correct phase. This is the main reason to use a non iterative method in the DSP in the presence of pile-up.

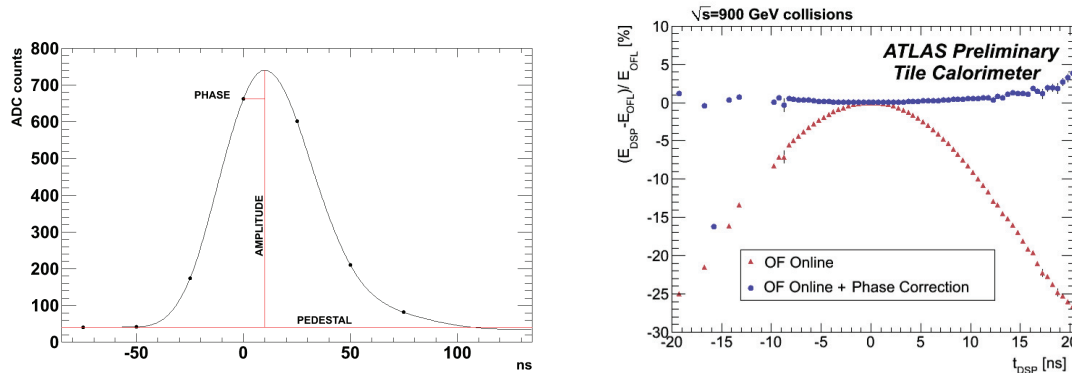


Fig. 3. (a) TileCal pulse shape and Optimal Filtering magnitudes; (b) relative difference between the energy reconstructed with the DSP Non Iterative and the offline Iterative methods as a function of the phase reconstructed by the DSP showing the bias in the energy reconstruction due to the phase variations (red). The bias can be corrected applying a second order correction using the phase of the pulse (blue).

3. Optimal Filtering Validation

During the ATLAS commissioning phase and with the first collisions at low luminosity it was possible to transmit from the DSP the digital samples for all the channels together with the reconstructed magnitudes. The digital samples were offline reconstructed and the result was used as reference to validate the online reconstruction. We used different reconstruction methods for the offline reconstruction.

3.1. Validation with offline Non Iterative algorithm

The offline Non Iterative Optimal Filtering method is an implementation of the algorithm used in the DSP but using floating point instead of fixed point arithmetic. Therefore, some minor differences are expected between both reconstruction results. The same set of weights retrieved from a centralized database is used online and offline in order to guarantee similar reconstruction conditions.

The maximum expected difference due to fixed point arithmetic is, in this case, proportional to the calibration constant (from ADC to MeV) and therefore changes from channel to channel. Fig 4a shows the absolute difference between the signal amplitude calculated on collision data with the Non Iterative Optimal Filtering Algorithm online (E_{DSP}), and offline ($E_{OFL\ NI}$). The red dashed lines indicate the maximum expected precision for standard functioning channels and contain 99% of the channels. The blue lines indicate the expected precision for the highest calibration constant.

Concerning the phase reconstruction since the same Non Iterative algorithm is used online and offline the expected difference is due to fixed point arithmetic and to the Look-up-Table (LUT) used in the DSP to implement the division by the energy (Equation 1). Fig 4b shows the absolute difference between the phase reconstructed online (DSP) and offline without iterations (OFL NI) as a function of the phase reconstructed offline for collisions data and for channels with energy reconstructed by the DSP above 50 MeV. We observe that the LUT effect is enhanced for larger phases but differences are within ± 1.5 ns in the $[-25, +25]$ ns range.

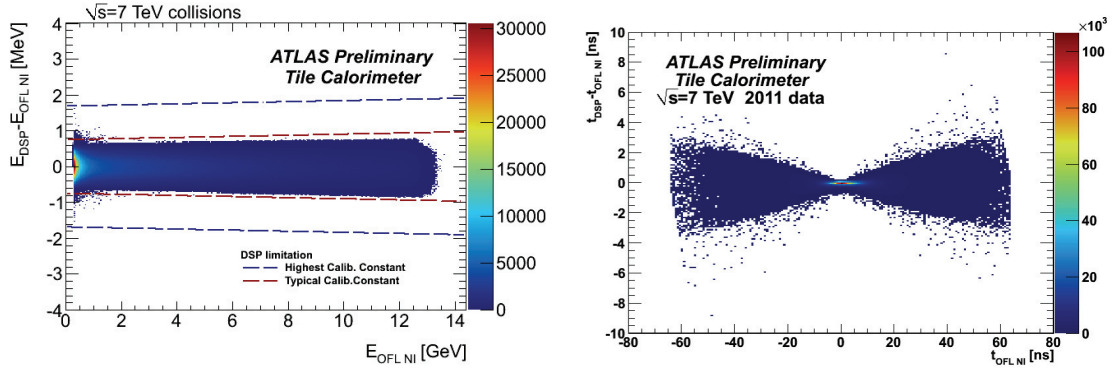


Fig. 4. (a) Absolute difference between the signal amplitude calculated on Collision data with the Non Iterative Optimal Filtering algorithm online (E_{DSP}), and offline ($E_{\text{OFL NI}}$) as a function of the energy reconstructed offline; (b) absolute difference between phase reconstructed online (DSP) and offline without iterations (OFL NI) as a function of phase reconstructed offline for collisions data (7 TeV) for Tile Calorimeter channels with energy reconstructed by the DSP above 50 MeV.

3.2. Validation with Iterative algorithm

The offline Iterative algorithm (used for cosmic rays and during commissioning for detector timing studies) uses two initial iterations of the optimal filtering algorithm to estimate the phase of the pulse. The result is used to select from a database the correct set of weights to be used in a third iteration to obtain the final signal amplitude and phase. Therefore, the result is not affected by phase variations in the pulse on an event-by-event basis. The comparison between the online Non Iterative method and the offline Iterative method shows the deviation produced by phase variations (Fig 3b). The bias can be corrected by applying a factor dependent on the reconstructed signal phase as discusses in section 3.1. In the phase range $[-10, 10]$ ns the average difference between the offline and online reconstruction is within 1%.

The phase reconstruction in the DSP is also affected by the amplitude deviation due to phase variations. Fig 5 shows the correlation between the phase reconstructed by the DSP and by the offline Iterative method. We observe a good correlation between both methods in the ± 1 bunch crossing range. It should be noted that 95% of the pulses are within the $[-5, 5]$ ns range.

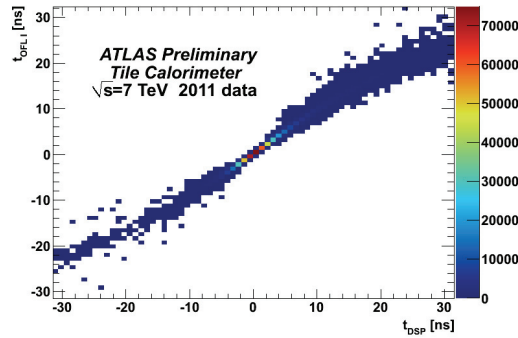


Fig. 5. Correlation between phase reconstructed online (DSP) and Offline with Iterative algorithm (OFL I) for collisions data (7 TeV) for Tile Calorimeter channels with energy reconstructed offline with iterations above 300 MeV.

3.3. Reconstruction in the presence of pile-up interactions

The time spacing between bunches has recently been shrunk to 50 ns increasing the pile-up contribution. The iterative method can reconstruct signals generated by a different bunch crossing as it can be seen from the two peaks at ± 50 ns on Fig.6a. On the other hand, the Optimal Filtering Non Iterative algorithm as implemented in the DSP (Fig 6b) uses a well defined signal phase for each channel and is not very sensitive to the presence of signals from other bunch crossing (out of time Minimum Bias pileup noise). Currently the Non Iterative method is being used for offline reconstruction in TileCal and the parabolic correction is applied for phase variations within 1 bunch crossing.

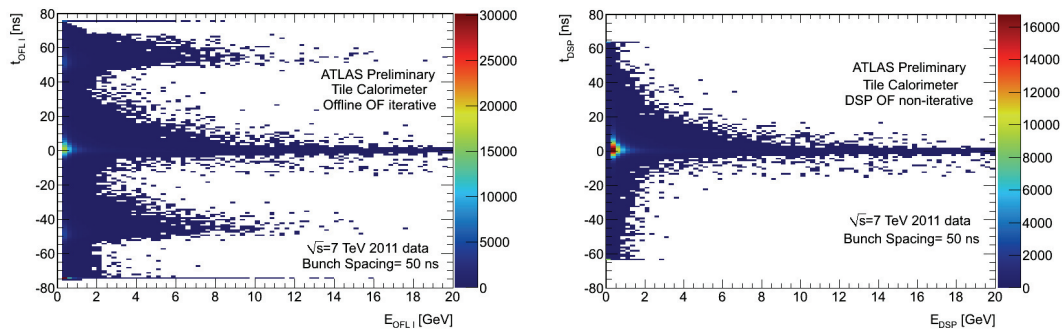


Fig. 6. The plots show the phase as a function of the energy reconstructed at the channel level in the Tile Calorimeter using (a) the offline Iterative and (b) the DSP Non Iterative methods applied to 2011 collision data. A run with train of bunches crossing every 50 ns is used. A cut of 200 MeV is used to reduce the contribution of the electronic noise.

4. Conclusions

The TileCal online signal reconstruction performed in the DSPs has been validated during the commissioning phase and with the first LHC collisions. It was validated using the offline reconstruction as reference. The results are compatible with the expected differences between the fixed point arithmetic used in the DSP and the floating point arithmetic used for the offline reconstruction. Currently the DSP Optimal Filtering reconstruction is used in the High Level trigger system. In addition, the DSP transmits

the digital samples for pulses above a programmable threshold. These samples are reconstructed offline with Optimal Filtering running in floating point arithmetic processors. Therefore, it is used a mixture of DSP and offline reconstructions for physics analysis.

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